Spin-Density Matrix Elements for γp→K^{*0}Σ^{+} at E_{γ}=1.85–3.0 GeV with Evidence for the κ(800) Meson Exchange

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Phys. Rev. Lett. **108**, 092001 — Published 27 February 2012

DOI: 10.1103/PhysRevLett.108.092001

Spin-density matrix elements for $\gamma p \to K^{*0}\Sigma^+$ at $E_\gamma = 1.85 - 3.0$ GeV with evidence for the $\kappa(800)$ meson exchange

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The exclusive reaction $\gamma p \to K^+\pi^-\Sigma^+$ was measured for the first time using linearly polarized photons at beam energies from 1.85 to 2.96 GeV. Angular distributions in the rest frame of the $K^+\pi^-$ system were fitted to extract spin-density matrix elements of the K^{*0} decay. The measured parity spin asymmetry shows that natural parity exchange is dominant in this reaction. This result clearly indicates the need for t-channel exchange of the $\kappa(800)$ scalar meson.

PACS numbers: 13.60.Rj, 13.88.+e, 24.70.+s, 25.20.Lj

It is well known in the quark model of hadrons that mesons are found in groups of 8+1 (an octet plus a singlet). In the simplest quark model [1], the lightest meson octet has 3 mesons with no strange quark, 4 mesons containing either a strange quark (s) or a strange antiquark ($\bar{s}$), and one meson with a dominant $s\bar{s}$ content. The ground-state pseudoscalar meson octet is well-established, and consists of three pions, four kaons, and an eta-meson. However, for the higher-mass mesons, the assignments are not clear. For example, the Particle Data Group (PDG) [2] states that identification of the scalar mesons is "a long-standing puzzle". In particular, the κ-meson (presumed to be part of the lowest-mass scalar meson octet) with a resonance pole at about 800 MeV is seen in many phenomenological analyses [3–9], yet its existence is still controversial.

The quantum numbers of the κ-meson are $J^P = 0^+$ and $I = 1/2$. The κ is considered to be the scalar partner to the kaon in an analogous way as the σ-meson (also called the $f_0(600)$) is the scalar partner to the η-meson. The problem with establishing the existence of the σ or κ mesons is, in part, that their resonance widths are very broad (about 400 MeV or even higher). Hence they are difficult to see in partial wave analyses of meson scattering data. In the case of D-meson decay [4], the decay amplitude of $D^+ \to K^-\pi^+\pi^+$ requires an additional $K\pi$ resonance with the quantum numbers of the κ to get agreement with the data; including the κ improves the χ^2 of the theoretical fit to the data by a factor of 4. Very recently, stronger evidence has been found from fits to Dalitz plots of $K\pi\pi$ final states in D-meson decay [9]. However, because the κ in those analyses is a background, without a clear mass peak, additional evidence is desired before the κ meson can be firmly established.

As mentioned above, the light scalar mesons are difficult to accommodate. The assignments for $J^{PC} = 0^{++}$ are filled by the higher-mass $a_0(1450)$ and $f_0(1370)$ plus $f_0(1710)$ mesons, along with the $K^*(1430)$. In contrast, the light scalar mesons, consisting of the $a_0(980)$ and $f_0(980)$ plus the σ are thought to be meson-meson [10, 11] or 4-quark states [12, 13], and so are not included in the classical quark model picture. The $a_0(980)$ and $f_0(980)$

are firmly established, but their interpretation as exotic 4-quark states is still in question. More information on the structure of these scalar mesons is desired [14].

The σ meson has a width almost equal to its mass, and certainly cannot be described as a typical Breit-Wigner resonance. The κ is thought to be similar, with a pole mass of about 800 MeV and a width about half as large ($\sim$ 400 MeV). Definitive evidence for the σ or κ mesons would provide a significant advance in the understanding of possible multi-quark states.

Here, we report on the linear polarization observables for K^* photoproduction measured using a proton target. These observables, the spin-density matrix elements, have been shown to be sensitive to κ-meson exchange. The one theoretical model [15] currently available predicts sizable forward-angle polarization effects in the energy range accessible at the SPring-8/LEPS facility. In particular, Ref. [15] predicts that the $\kappa(800)$ contributes to K^* photoproduction through t-channel exchange, which dominates at forward scattering angles. Also, the contribution of the $\kappa(800)$ for $K^{*0}\Sigma^+$ photoproduction is predicted to be relatively larger than that for $K^{*+}\Lambda$ photoproduction [16]. The theoretical model [15] fits the CLAS data [17] and the CBELSA/TAPS data [18] fairly well but both data lack good statistics at forward angles. No polarization measurement for this reaction has been previously reported in the literature.

In general, K^* photoproduction is different from other neutral vector mesons in that Pomeron exchange is absent in the photoproduction of strange mesons. Hence the reaction mechanism for K^{*0} photoproduction is different from the case of the neutral nonstrange mesons (ρ^0, ω and ϕ) where the t-channel has a strong contribution from Pomeron exchange. At low energies, meson exchange also contributes to the t-channel ρ and ω photoproduction, but Pomeron exchange quickly becomes dominant as the photon energy increases.

For K^{*0} photoproduction, the ambiguities in the theoretical models at forward angles are rather limited. A single diagram dominates the t-channel, where a K^0 is exchanged and absorbs the photon through the $M1$ multipolarity. The hadronic coupling of the K^0 to the proton, $g_{KN\Sigma}$, is already constrained from kaon scattering data [19]. Exchange of a K^{*0} in the t-channel is suppressed, since only higher (non-spin-flip) multipolarities can contribute to this diagram [15]. Also, the contact term is proportional to the vector meson charge, and vanishes for the neutral K^{*0} production. However, a scalar meson can contribute to the t-channel for K^{*0} photoproduction, whereas it is forbidden by parity and angular momentum for kaon photoproduction. By comparing the data measured here with two theoretical models, one with minimal κ-exchange and the other with substantial κ-exchange, we can test for the existence of the $\kappa(800)$.

The parity spin asymmetry [15], given in terms of the spin density matrix elements by $P_\sigma = 2\rho^1_{1-1} - \rho^1_{00}$, is shown in Ref. [15] to be particularly sensitive to the role of κ-exchange, especially at forward angles. In the case of scalar κ exchange, the parity spin asymmetry is positive, whereas calculations without the κ (with pseudoscalar kaon exchange only) have negative parity spin asymmetry. The present data provide the first-ever reported parity spin asymmetry for K^{*0} photoproduction.

The experiment was carried out using the LEPS detector at the SPring-8 facility in Japan. The photon beam was produced by the laser backscattering technique [20] using a 275 nm laser, with wavelengths in the deep-UV region, to produce Compton-scattered photons in the range of 1.5 to 2.96 GeV. The laser light was linearly polarized with an average polarization of 98 %. The polarization is conserved at the Compton edge, and decreases in a calculable way as the photon energy decreases. The

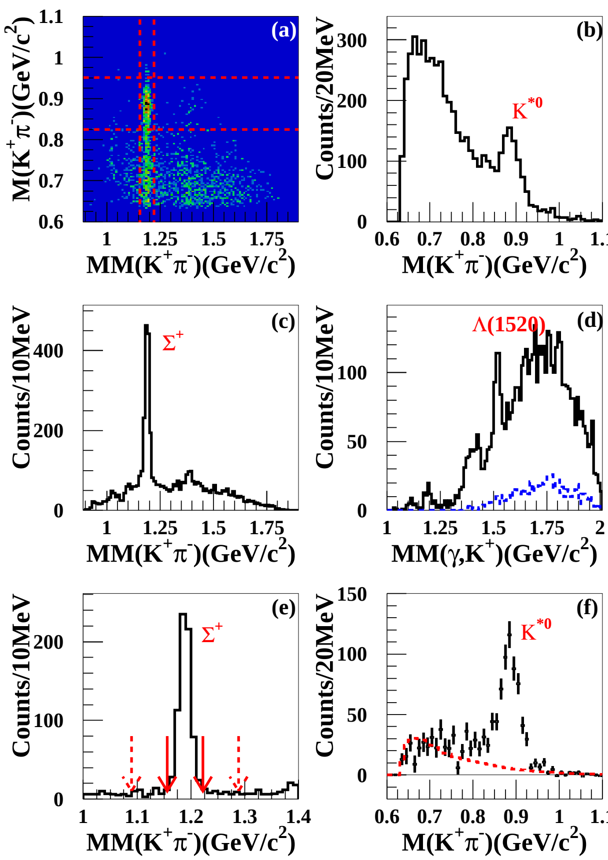

FIG. 1: (a) Scatter plot of the missing mass of the $K^+\pi^-$ system versus the invariant mass of the $K^+\pi^-$ system; (b) and (c) are the projected spectra for the invariant mass and missing mass distributions, respectively; (d) missing mass of the K^+ (with a π^- detected), and the lower dashed histogram indicates the final even selection within 3σ of the Σ^+ peak and the K^{*0} peak; (e) missing mass distribution with solid arrows around the signal region (K^{*0} peak) and dashed arrows showing the outside of the side-band regions; (f) same as (b), but with a cut on the Σ^+ peak after the side-band background subtraction, and the overlaid dashed line shows the estimated Y^* background.

photon beam was incident on a 15 cm liquid hydrogen target, where K^+ and π^- particles were produced and then passed through the LEPS spectrometer [20]. For this experiment, no Cherenkov detector was used so that π^- with higher momentum could be detected. Instead, a narrow scintillator bar was placed downstream of the tracking chambers, in the bend plane of the spectrometer, to remove e^+e^- pairs from the trigger. Otherwise, the standard configuration of the LEPS detector [20] was used.

To identify candidate events, a K^+ track and a π^- track were required using standard particle identification methods [20]. The vertex of the K^+ and π^- tracks were required to be in the region of the LH_2 target. Very rarely, the K^+ track could be a mis-identified π^+, and these few events were removed if the missing mass of the two tracks, both given the pion mass, had the mass of the proton.

Mass spectra, calculated from the measured 4-vectors of detected K^+ and π^-, are shown in Fig. 1: (a) shows a two-dimensional plot of a missing mass of the $K^+\pi^-$ system ($MM(K^+\pi^-)$), calculated using the tagged photon energy (measured from the recoil electron energy) and the target proton mass, versus an invariant-mass of the $K^+\pi^-$ system ($M(K^+\pi^-)$). The dashed lines represent a 3σ window for $K^{*0}\Sigma^+$ production, where σ is the measured resolution of the peak.

Peaks for the K^{*0} and Σ^+ are clearly seen in the projected spectra for invariant-mass (Fig. 1b) and missing mass (Fig. 1c). There is background under these peaks, which is primarily from 3-body production mechanisms, with a small amount of Y^* production such as the $\Lambda(1520)$. Evidence for the Y^* background can be seen in the missing mass of the K^+ (Fig. 1d) for the same events as upper plots. However, very little Y^* background remains after selecting a region around the K^{*0} peak and Σ^+ peak (shown by the lower histogram in Fig. 1d). When selection on the K^{*0} peak is applied (horizontal dashed lines in Fig. 1a), a clear Σ^+ peak is seen in the $MM(K^+\pi^-)$ (see Fig. 1e). A smooth background lies below the Σ^+ peak, shown by the dashed line. A subtraction was performed to remove background from the $M(K^+\pi^-)$ spectrum, using events in the side-band regions (from dashed arrow to solid arrow in both sides of the Σ^+ peak as shown in Fig. 1e). The plot in the Fig. 1f shows the $M(K^+\pi^-)$ spectrum after selection on the Σ^+ peak plus side-band subtraction. The overlaid red dashed line shows the estimated Y^* background, with only a small background remaining under the K^{*0} peak. For the final event selection, we place 3σ cuts around both the Σ^+ peak and the K^{*0} peak.

The decay angular distribution can be expressed in terms of nine spin-density matrix elements and linear polarization of the photon beam energy [21]. We extracted the spin-density matrix elements using an unbinned extended maximum likelihood fit (see [22] for details) in the Gottfried-Jackson (GJ) frame and helicity frame and the beam energy region from 1.85 (threshold for $K^*\Sigma$ production) to 2.96 GeV. The K^* production angle $\cos\theta_{K^*}$ ranges from 0.6 to 1.0 and its average value is 0.9115. The measured spin-density matrix elements are listed in Table I. In the case of helicity conservation, the decay asymmetry ρ^1_{1-1} reflects the relative contributions of natural parity ($\rho^1_{1-1} = -0.5$) and unnatural parity ($\rho^1_{1-1} = 0.5$) processes.

Figs. 2 and 3 show decay angular distributions for a sum of horizontal and vertical beam polarizations with

TABLE I: Measured spin-density matrix elements by an unbinned extended maximum likelihood fit with event selection at very forward angle in the GJ frame and helicity frame, respectively, averaged over photon energies from 1.85 to 2.96 GeV.

$\hat{\rho}_s$	GJ frame	helicity frame
ρ^0_{00}	0.155 ± 0.051	0.082 ± 0.025
ρ^0_{10}	0.108 ± 0.068	-0.023 ± 0.021
ρ^0_{1-1}	0.090 ± 0.191	0.037 ± 0.040
ρ^1_{11}	0.031 ± 0.052	-0.016 ± 0.049
ρ^1_{00}	-0.140 ± 0.074	-0.049 ± 0.044
ρ^1_{10}	-0.088 ± 0.039	0.000 ± 0.034
ρ^1_{1-1}	0.322 ± 0.068	0.355 ± 0.057
ρ^2_{10}	0.127 ± 0.051	-0.038 ± 0.035
ρ^2_{1-1}	-0.357 ± 0.063	-0.395 ± 0.051

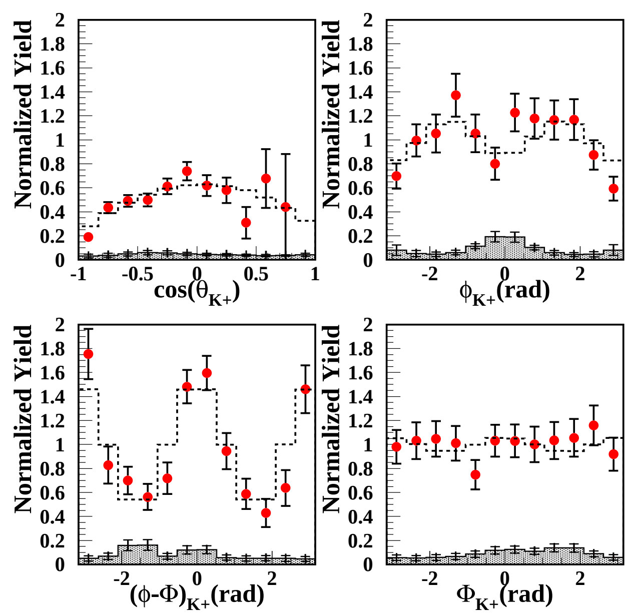

FIG. 2: Decay angular distributions of $\cos\theta_{K^+}$, ϕ_{K^+}, $(\phi-\Phi)_{K^+}$, and Φ_{K^+} in the GJ frame for the sum of vertical polarization and horizontal polarization after acceptance correction. The dotted line shows Monte-Carlo data using the measured spin-density matrix elements, while the overlaid black histogram indicates the Y^* background yield from a Monte-Carlo simulation.

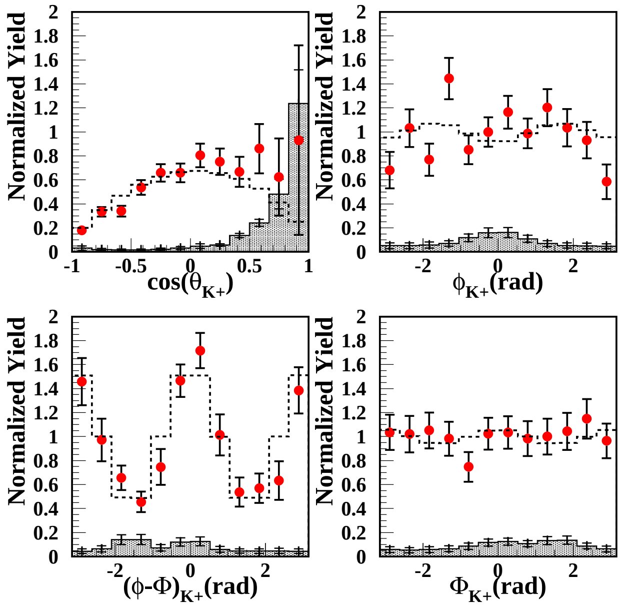

FIG. 3: Decay angular distributions in the helicity frame. Notations are the same as in Fig. 2.

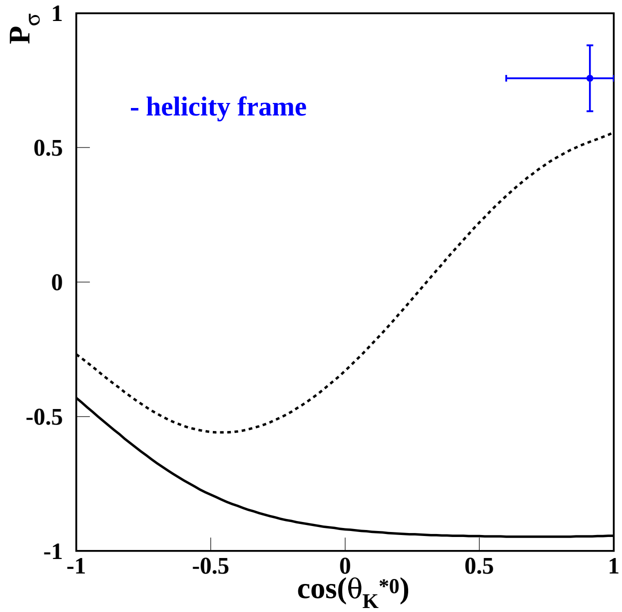

FIG. 4: Parity spin asymmetry ($P_\sigma = 2\rho^1_{1-1} - \rho^1_{00}$) in the helicity frame. The data point is averaged over photon energies from 1.85 to 2.96 GeV. The solid (dashed) line is the result of Model I (Model II) of Ref. [15] at $E_\gamma = 2.5$ GeV. Model I has almost no contribution from κ-exchange, whereas Model II includes substantial κ-exchange.

only a single variable, $\cos\theta_{K^+}$, ϕ_{K^+}, $(\phi-\Phi)_{K^+}$ and Φ_{K^+}, in the GJ frame and helicity frame [23]. The data have been corrected for detector acceptance by a Monte Carlo simulation, using the GEANT3 software [24, 25]. The event generators used the measured spin-density matrix elements, and it was checked that output of the simulations (when run through the extended maximum likelihood fit) reproduced the input. The dotted lines indicate Monte Carlo distributions with the measured spin-density matrix elements in the GJ frame and helicity frame. Black histograms indicate the estimated Y^* background in the reconstructed Monte Carlo distribution. In the helicity frame, the $\cos\theta_{K^+}$ distribution is enhanced at forward angles due to the Y^* production. However, the Y^* background there is actually small; the apparent enhancement near $\cos\theta_{K^+} \simeq 1$ is because the spectra are corrected for the K^{*0} acceptance, which is very small in that angular region. The few counts of Y^* background there has little effect on the extraction of the spin-density matrix elements, which is heavily weighted by events with $\cos\theta_{K^+} < 0.5$. (Angular distributions will be published in a later paper.)

The parity spin asymmetry ($P_\sigma = 2\rho^1_{1-1} - \rho^1_{00}$) is estimated to be 0.784 ± 0.154 in the GJ frame and 0.758 ± 0.123 in the helicity frame over the angular range shown by the horizontal error bar in Fig. 4. The good agreement between the parity spin asymmetry extracted in both frames is expected; the variation of these two results is a good indication of the systematic uncertainty, as the Y^* background has a different distribution in the two frames. Other systematic uncertainties, such as the beam polarization, are much smaller than the quoted uncertainties. The large positive asymmetry shows that the natural parity exchange is the dominant process at forward angles. The dashed (solid) line in Fig. 4 is the result with Model I (Model II) of Ref. [15] at $E_\gamma = 2.5$ GeV. The data clearly favors Model II, which includes a substantial contribution from natural-parity κ-exchange. The mass and width of the κ-meson are parameters of the theoretical model, and are not directly measured by the present data.

In summary, the photoproduction of the $\gamma p \to K^{*0}\Sigma^+$ reaction was measured at the LEPS detector at forward production angles and energies from 1.85 to 2.96 GeV, using a linearly polarized photon beam at SPring-8. The parity spin asymmetry measurement is a good probe to study the effect of κ meson exchange in $K^{*0}\Sigma^+$ production. We present spin-density matrix elements using an unbinned extended maximum likelihood fit in the GJ frame and the helicity frame. The parity spin asymmetry ($P_\sigma = 2\rho^1_{1-1} - \rho^1_{00}$) has a large positive value, showing that natural-parity exchange is dominant at forward angles for $K^{*0}\Sigma^+$ photoproduction. A natural explanation for the natural-parity exchange would be t-channel exchange of a scalar meson with strangeness, which is consistent with the κ meson. The existence of this meson would be a good candicate to complete the lowest-mass scalar meson octet.

The authors gratefully acknowledge the contributions of the staff at the SPring-8 facility. Thanks are due to A. Hosaka for valuable theoretical discussions. This research was supported in part by the US National Science Foundation, the Ministry of Education, Science, Sports and Culture of Japan, the National Science Council of the Republic of China, and the National Research Foundation in Korea (2009-0089525 and 2011-220-C00011).

[1] M. Gell-Mann and Y. Ne'eman, *The Eightfold Way*, (W.A. Benjamin, New York, 1964).
[2] K. Nakamura *et al.*, (Particle Data Group), J. Phys. G **37**, 075021 (2010).
[3] D.V. Bugg, Phys. Lett. B **572**, 1 (2003).
[4] E.M. Aitala *et al.*, Phys. Rev. Lett. **89**, 121801 (2002).
[5] D. Epifanov *et al.*(Belle collaboration), Phys. Lett. B **654**, 65 (2007).
[6] M. Bischofberger *et al.*(Belle collaboration), Phys. Rev. Lett. **107**, 131801 (2011).
[7] P. del Amo Sanchez *et al.*(BaBar collaboration), Phys. Rev. Lett. **105**, 081803 (2010).
[8] B. Aubert *et al.*(BaBar collaboration), Phys. Rev. D. **78**, 034023 (2008).
[9] A. Poluektov *et al.*(Belle collaboration), Phys. Rev. D. **81**, 112002 (2010).
[10] J.A. Oller and E. Oset, Nucl. Phys. A **620**, 438 (1997); Erratum *ibid.* A **652**, 407 (1999).
[11] J.R. Pelaez, Phys. Rev. Lett. **92**, 102001 (2004).
[12] R. Jaffe, Phys. Rev. D **15**, 267 (1977).
[13] M. Alford and R.L. Jaffe, Nucl. Phys. B **578**, 367 (2000).
[14] C. Amsler and N. Tornqvist, Phys. Rep. **389**, 61 (2004).
[15] Y. Oh and H. Kim, Phys. Rev. C **74**, 015208 (2006).
[16] S. Ozaki, H. Nagahiro and A. Hosaka, Phys. Rev. C **81**, 035206 (2010).
[17] I. Hleiqawi *et al.*(CLAS collaboration), Phys. Rev. C **75**, 042201 (2007).
[18] M. Nanova *et al.*(CBELSA/TAPS collaboration), Eur. Phys. J. A **35**, 333 (2008).
[19] T. Mart and C. Bennhold, Phys. Rev. C **61**, 012201 (1999).
[20] T. Nakano *et al.*, Nucl. Phys. A **670**, 332 (2000); *ibid*, A **721**, 112 (2003).
[21] K. Schilling, P. Seyboth, and G. Wolf, Nucl. Phys. B **15**, 397 (1970).
[22] W.C. Chang *et al.* (LEPS Collaboration), Phys. Rev. C **82**, 015205 (2010).
[23] T. Mibe *et al.* (LEPS Collaboration), Phys. Rev. Lett. **95**, 182001 (2005) ; T. Mibe, Ph.D. thesis. Osaka University, (2004).
[24] CERN Application Software Group, GEANT3.2, CERN Program Library writeup Report No. W5013, (1994).
[25] M. Sumihama *et al.* (LEPS Collaboration), Phys. Rev. C **73**, 035214 (2006).